

# Enhancement of Stabilization Control in Remote Robot System with Force Feedback

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## Abstract

In this paper, we deal with a remote robot system in which a user can operate an industrial robot with a force sensor at a remote location by using a haptic interface device. We apply a method using the wave filter together with the phase control filter which was previously proposed by the authors to the remote robot system for stabilization control. We also propose a method to enhance the haptic quality. By experiment, we demonstrate the effectiveness of the proposed method. We compare the proposed method with the conventional method quantitatively and clarify which domains the proposed method is applied to more effectively.

## Keywords

Remote Robot System, Stabilization Control, Force Feedback, Quality, Experiment

## 1. Introduction

Recently, a number of researchers focus on studies of remote robot systems with force feedback [1] [2] [3]. By using force feedback, since users can touch remote objects and feel the shape, weight, and softness of the objects, the efficiency and accuracy are expected to be largely improved [4]. However, when the haptic information such as position and/or force information is transmitted over a Quality of Service (QoS) [5] non-guaranteed network like the Internet, QoS may seriously deteriorate [3] [4]. Furthermore, in the remote robot systems, when the network delay increases, the reaction force becomes larger, and instability phenomena such as vibrations of the robot and device may occur [6] [7] [8]. To solve the problems, we need to carry out stabilization control and QoS control together [4].

There are many studies which focus on remote robot systems with force feedback [9] [10]. In [9], the authors assess the Quality of Experience (QoE) [11] about the operability of a haptic interface device for work in which a user operates an industrial robot with a force sensor at a remote location by using the haptic interface device while watching video. They investigate the influence of network delay on the operability and the effect of the adaptive reaction force control [12]. As a result, the control is effective for the remote robot system with force feedback. In [10], Banthia *et al.* make a prototype telerobotic system for live transmission line maintenance. In the system, a user can operate a haptic interface device at a local terminal to control a remote robot arm. Then, the user tries to do the maintenance by controlling the remote robot arm. They also investigate the difference in force feedback control (unilateral or bilateral control) by experiment. However, in the papers, they do not carry out stabilization control for the remote robot systems with force feedback. On the otherhand, Miyoshi *et al.* propose stabilization control which uses the wave filter together with the phase control filter for a haptic telecontrol system in which 1-DoF haptic interface devices are employed in [13] and [14].

In this paper, we mainly focus on the stabilization control. In a preliminary experiment, we applied out the wave filter together with the phase control filter to the remote robot system with force feedback for stabilization control, and investigated the effect of the stabilization control. In order to clarify the effect of the conventional stabilization control, we pushed a soft object (rubber ball). As a result, we found that the control is effective [7]. However, we found that the control is less effective for hard objects. Therefore, we propose a method in which we incorporate a phase lead compensation filter and a phase lag compensation filter with the conventional control in [7] to achieve stabilization and enhance the haptic quality and investigate the effect of the proposed method and clarify the effective domains by comparing the proposed method with the conventional method. This paper has the following two main contributions: 1) we propose an enhancement method of stabilization control to improve the haptic quality; 2) we also clarify which domains the proposed method and conventional method are applied to more effectively.

The remainder of this paper is organized as follows. Section 2 describes the remote robot system with force feedback. Section 3 introduces the conventional stabilization control and the proposed method. Section 4 explains assessment methods, and assessment results are presented in Section 5. Finally, Section 6 concludes the paper.

## 2. Remote Robot System with Force Feedback

### 2.1. System Configuration

The configuration of the remote robot system with force feedback is shown in **Figure 1**. The system consists of two terminals called the master terminal and slave terminal. Each of the terminals consists of two PCs, and the PCs are connected

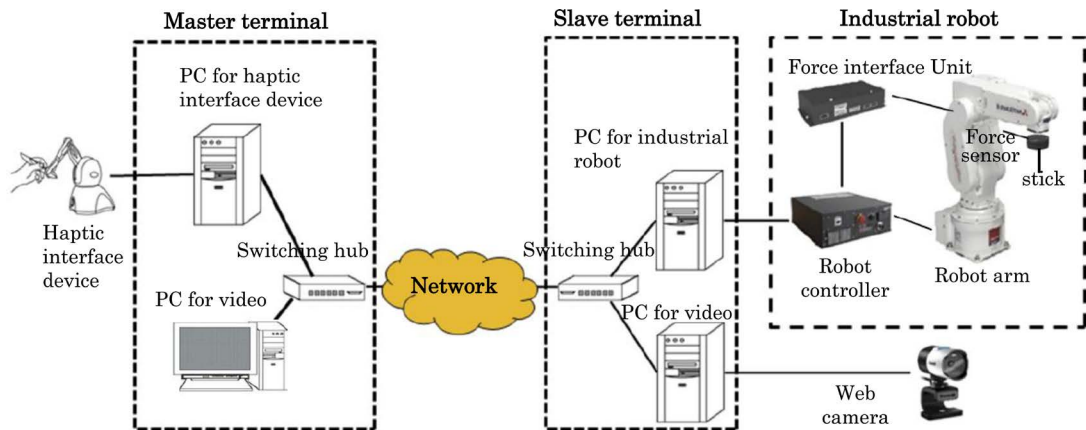


Figure 1. Configuration of remote robot control system with haptics.

to each other via a switching hub.

At the master terminal, a haptic interface device (Geomagic Touch [15]) is connected to PC for haptic interface device, and another PC is used for video. At the slave terminal, one of the two PCs is used for web camera (produced by Microsoft Corp., and video resolution is  $1920 \times 1080$  pixels), and the other PC is used for industrial robot. The industrial robot consists of a robot arm (RV-2F-D by Mitsubishi Electric Corp. [16]), a robot controller (CR750-Q [16]), and a force sensor (1F-FS001-W200 [17]). The force sensor is attached to the surface of the flange of the robot arm. The force sensor is connected to the robot controller via the force interface unit. In order to investigate the effect of the proposed method, we handle objects (balls) with different types of softness in this paper.

## 2.2. Remote Operation

A user at the master terminal can operate the industrial robot at the slave terminal by using the haptic interface device while watching video (coding scheme: Motion JPEG, average bit rate: 4.5 Mbps). The default position of the haptic interface device is set to the origin, and the position corresponds to the default position of the industrial robot [9].

The master terminal updates the position information, calculates the reaction force, and outputs the reaction force every millisecond. The master terminal also transmits the position information to the slave terminal by User Datagram Protocol (UDP). At the slave terminal, the command information which is based on the position information received from the master terminal is sent to the industrial robot every 3.5 milliseconds by the real-time control function [18]. The force information is also acquired by the real-time control function, and the information is transmitted to the master terminal by UDP.

The reaction force  $F_t^{(m)}$  applied to the haptic interface device at time  $t$  ( $t \geq 1$ ) is calculated as follows:

$$F_t^{(m)} = K_{\text{scale}} F_{t-1}^{(s)}$$

where  $F_{t-1}^{(s)}$  denotes the force received from the slave terminal, and  $K_{\text{scale}}$  is a

force scale which is set to 1 in this paper. Furthermore, since the maximum exertable force applied to the haptic interface device is 3.3 N, the reaction force is set to 3.3 N when the calculated force is larger than 3.3 N.

The position vector  $S_t$  of the industrial robot outputted at the time  $t (t \geq 2)$  is calculated as follows:

$$S_t = \begin{cases} M_{t-1}, & (\text{if } |M_{t-1} - M_{t-2}| \leq V_{\max}) \\ \frac{V_{\max}}{|M_{t-1}|} M_{t-1}, & (\text{otherwise}) \end{cases}$$

where  $M_{t-1}$  is the position vector of haptic interface device received from the master terminal, and  $V_{\max}$  is the maximum movement velocity. That is, in order to operate the robot arm safely, the maximum movement velocity is limited to  $V_{\max}$  ( $V_{\max} = 5 \text{ mm/s}$  in this paper).

### 3. Stabilization Control

#### 3.1. Conventional Method

In bilateral control systems, instability phenomena occur more easily as the network delay increases [6]. The reason is as follows: The master terminal calculates reaction force by using the force information received from the slave terminal, and updates the position based on the reaction force. The updated position is transmitted to the slave terminal and the slave terminal updates its position based on the position received from the master terminal. This means that there exists a mechanical closed loop. The phase delay of the loop increases when there exist network delays, and if the phase delay is larger than 180 deg, the system becomes unstable. This is an unpreventable problem when we use a network.

Therefore, one of solutions for the problem is to carry out stabilization control using the wave filter together with the phase control filter [6] which was previously proposed by the authors. The block diagram of the control is shown in Figure 2. In Figure 2,  $G_m(s)$  is the transfer function of the master terminal, and  $G_s(s)$  is that of the slave terminal;  $f_s$  is the force information which is transmitted to the mater terminal from the slave terminal, and  $f_m$  is the output force for the master terminal;  $x_m$  is the position vector obtained at the master terminal, and  $x_r$

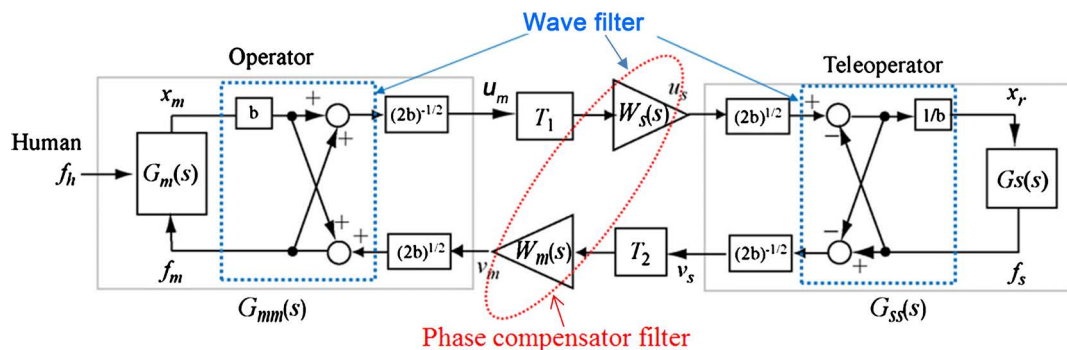


Figure 2. Block diagram of stabilization control.

is the position vector for the slave terminal;  $f_h$  is the force exerted from the user at the master terminal.

The wave filter includes the cross part and the coefficient  $b$ . The phase control filter includes  $W_s(s)$  and  $W_m(s)$ . For further details, the reader is referred to [9] and [13].

### 3.2. Enhancement Method

In a preliminary experiment, when we apply the conventional method to the remote robot system in the three axes, instability phenomena (vibrations of the robot and device) occurred when users tried to push a hard object such as a tennis ball.

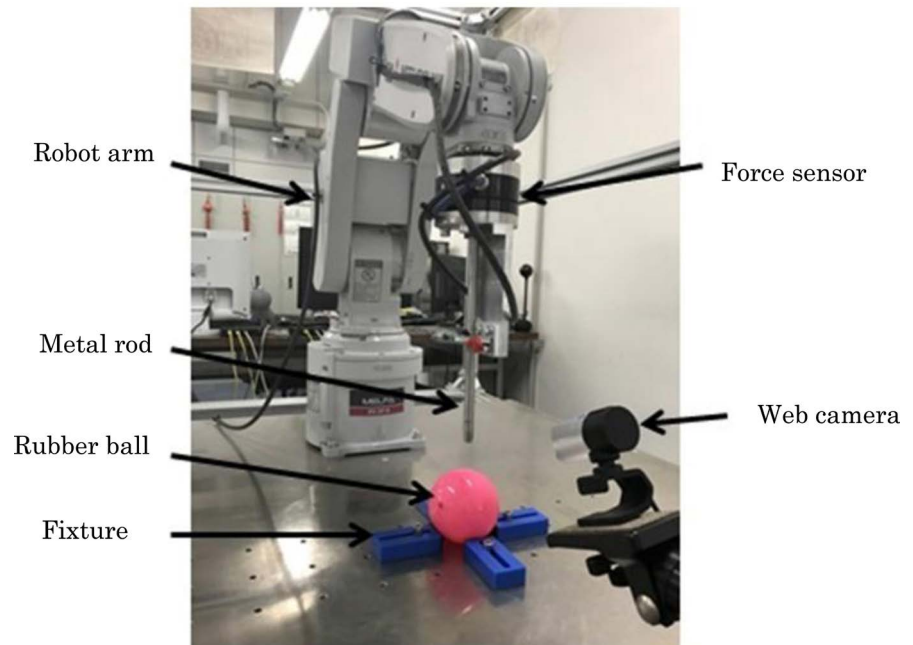
In order to solve the problem, we propose an enhancement method in which we incorporate a phase lead compensation filter  $(\frac{1}{2} \times \frac{0.25s+1}{0.08s+1})$  to  $G_m(s)$  and a phase lag compensation filter  $(\frac{1}{2} \times \frac{0.05s+1}{0.25s+1})$  to  $G_s(s)$ . The former filter is used to solve the phase lag caused by the second order integration from the force to position. In order to avoid instability due to the useless time of the industrial robot, the later filter is employed to lower the gain in high frequency ranges. Furthermore,  $W_s(s)$  and  $W_m(s)$  are set to  $\frac{1}{(0.03s+1)^2}$ , and  $b$  at the master

terminal is set to 0.3 and that at slave terminal is set to 0.6 (this means that the mapping ratio [6] from the work space of the haptic interface device to that of the industrial robot is 2:1).

### 4. Assessment Method

In our experiment, we employ a network emulator (NIST Net [19]) instead of the network of **Figure 1**. A metal rod is fixed at the tip of the force sensor which is attached to the surface of the flange of the robot arm. Four fixtures are setting on the top of rack which is used to fix the industrial robot arm to fix objects as shown in **Figure 3**. We generate a constant delay (called the additional delay in this paper) for each packet transmitted between the master and slave terminals. We handle two types of work (work 1 and work 2) to investigate the effect of proposed method. In work 1, each subject is asked to push a ball by operating the robot arm while watching video, and in work 2, the subject pushes a ball by operating the robot arm and identify what kind of the ball is pushed according to the softness without watching video. In the two types of work, the subject pushes the ball by the metal rod fixed at the robot arm.

In work 1, the subject pushes a ball from above and return back after pushing the ball for about 4 seconds, and he/she repeats the work three times (the subject is also asked to push the ball from the obliquely upward and the side, since the results are almost the same as those from above, we show only the results when the subjects push the ball from above). Because the effects of the conventional



**Figure 3.** Appearance of robot arm.

method for soft objects have been confirmed, we here deal with only a tennis ball, which is used as a hard object in the work. In order to compare the proposed method with the conventional method, we carry out the assessment by changing the constant delay as follows: 0 ms, 100 ms, 200 ms, 400 ms, and 800 ms. We measure the position of the haptic interface device, the position of the industrial robot, the output force of the haptic interface device, and the force obtained from the force sensor of the robot arm.

In work 2, we handle two balls with different softness as in [18]; one is a rubber ball (diameter: 70 mm), and the other is a soft tennis ball (diameter: 65 mm). Each subject pushes a ball from above and identifies the ball only by the softness he/she perceived. Therefore, we do not use the camera and the PCs for video in **Figure 1**. Furthermore, the robot arm is set to move only in vertical direction (the  $y$  axis) so that all the subjects can do the work under the same condition [20]. Also, we use papers with thickness of 5 mm under the soft tennis ball so that the height of the two balls is the same.

Before the experiment, each subject practices to push the two balls to confirm the softness about 1 minute without any additional delay. In the practice, the type of ball is told to the subject, and then he/she tries to push a ball from above five times for each ball.

In the experiment, the subject pushed a ball as in the practice to identify the ball only by perceived softness without telling what the ball is. Each ball was selected 5 times, and the order was random for each subject. We carried out the experiment by setting the constant delay to 0 ms, 50 ms, 100 ms, 200 ms, and 300 ms, and obtained the average of correct answer rate. The number of subjects (males) whose ages were between 21 to 25 is 15.

## 5. Assessment Results

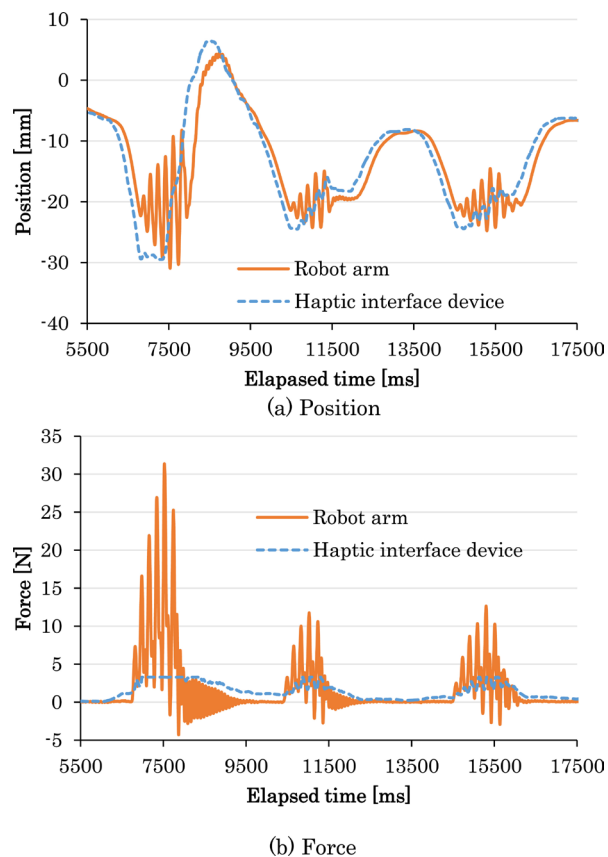
### 5.1. Work 1 (Push Ball) (3 Axes)

Experiment results of work to push a ball (tennis ball) are shown in **Figure 4** through **Figure 6**. The results of the conventional method are shown in **Figure 4**, and those of the proposed method are shown in **Figure 5**. Since the system with the conventional method becomes unstable, we show only the results of the proposed method when the additional delay is 800 ms in **Figure 6**. Also, because the results in the  $x$  and  $z$  axes are almost the same as those in the  $y$  axis, we demonstrate only the results in the  $y$  axis.

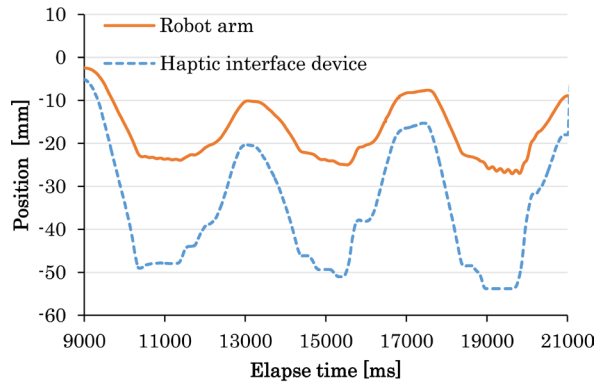
From **Figure 4**, we see that the instability phenomena (vibrations) occur when the subject tries to push the ball. This means that the system is instable. From **Figure 5**, we find that there are almost no vibrations; we can say that the system is stable. However, the position of the haptic interface device is twice as that of the industrial robot. This is because the coefficient  $b$  is set as described in 3.2.

From **Figure 6**, we can also notice that the system is stable as that in **Figure 5**. However, the position of the haptic interface device is delayed, and the delay is proportional to the network delay [8].

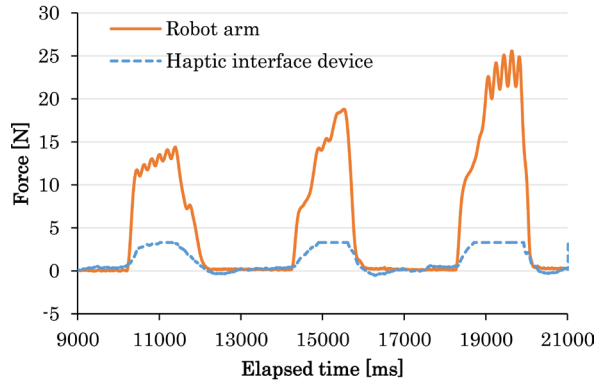
Furthermore, we carried out the experiment by using a soft tennis ball and a rubber ball, and we found that the stability can be attained by both conventional method and proposed method.



**Figure 4.** Position and force in conventional method ( $y$  axis, additional delay: 0 ms).

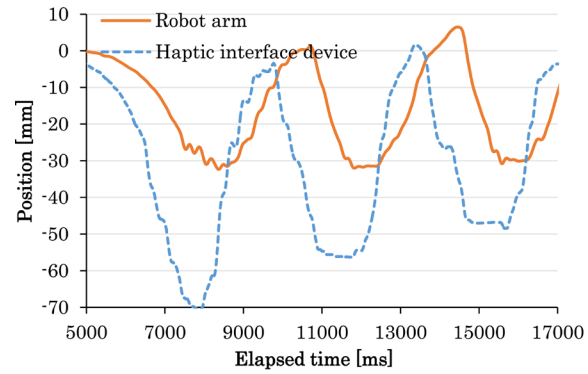


(a) Position

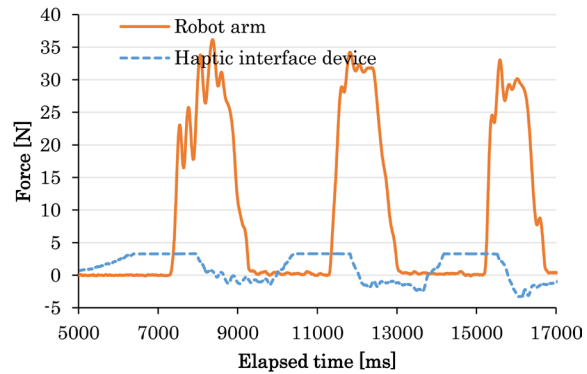


(b) Force

Figure 5. Position and force in proposed method ( $\gamma$  axis, additional delay: 0 ms).



(a) Position



(b) Force

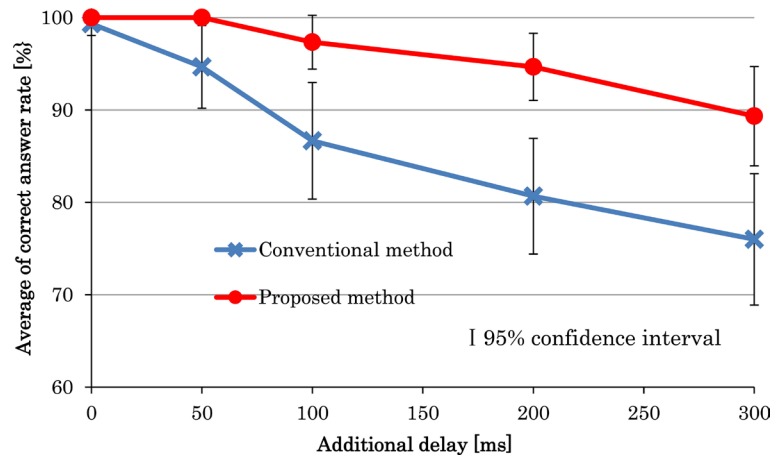
Figure 6. Position and force in proposed method ( $\gamma$  axis, additional delay: 800 ms).



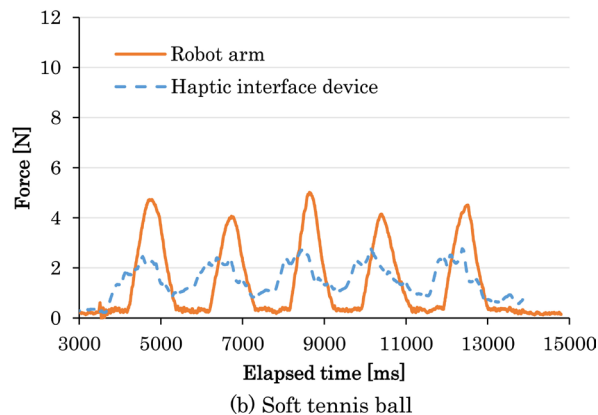
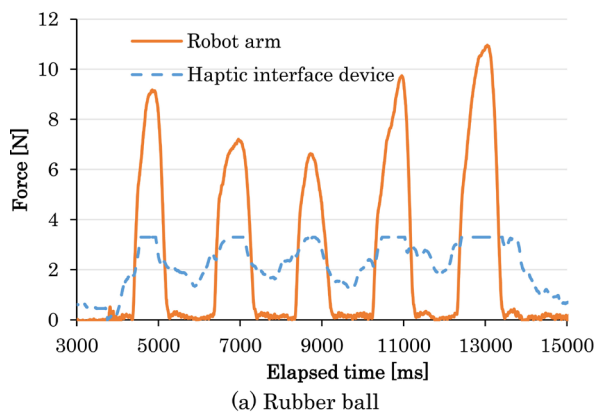
### 5.2. Work 2 (Ball Identification) (1 Axis)

The average of correct answer rate versus the additional delay is shown in **Figure 7**. We also plot the 95% confidence intervals in the figure.

From **Figure 7**, we notice that the average of correct answer rate of the proposed method is better than that of the conventional method. In order to clarify the reasons, we compare the force of the haptic interface device and that of the robot arm in the proposed method with those in the conventional method. The results are shown in **Figure 8** through **Figure 11**. From **Figure 8** and **Figure 9**,



**Figure 7.** Average of correct answer rate versus additional delay.



**Figure 8.** Force in conventional method (additional delay: 0 ms).

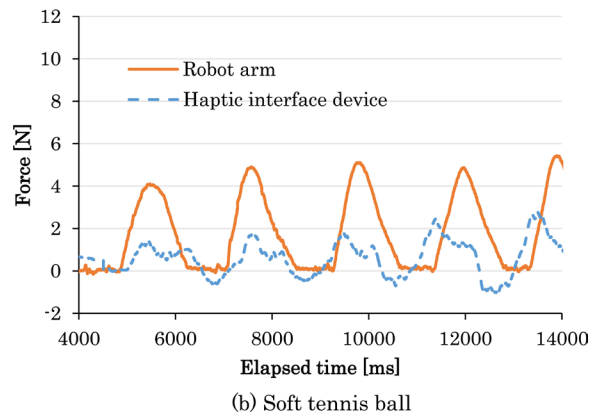
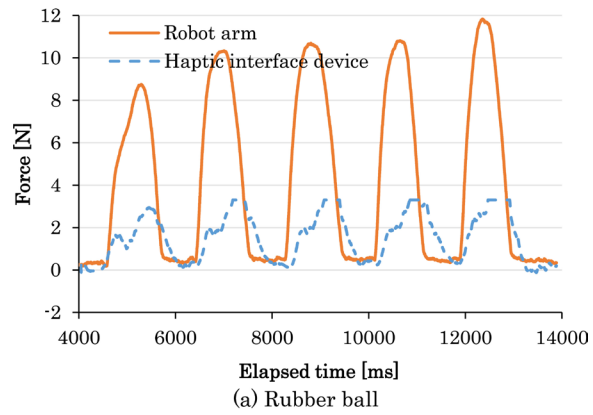


Figure 9. Force in proposed method (additional delay: 0 ms).

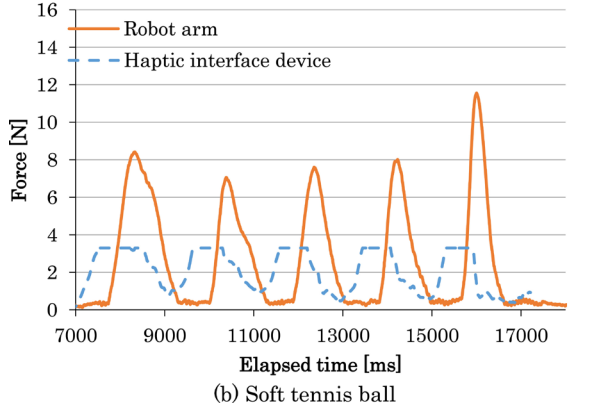
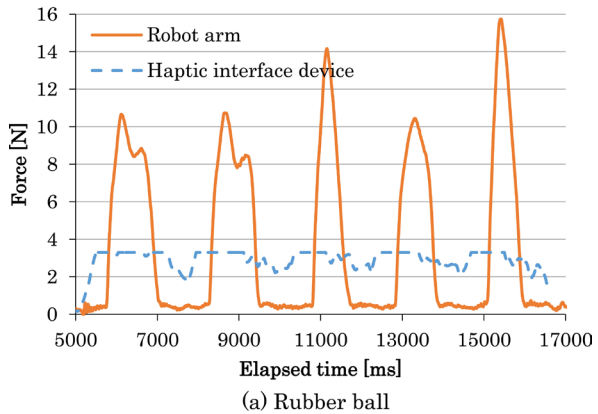
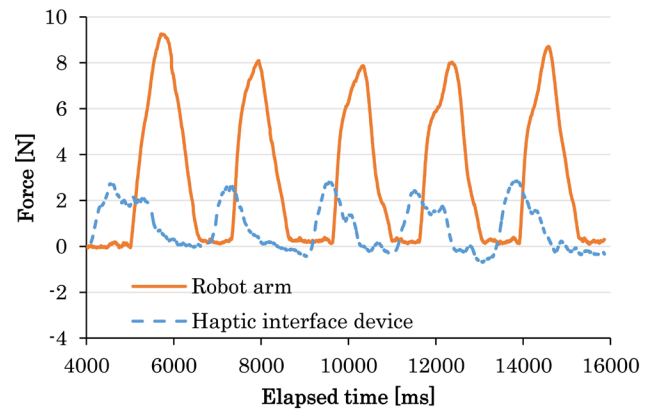
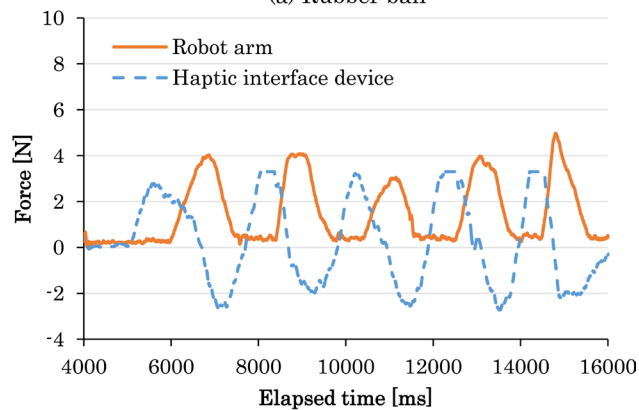


Figure 10. Force in conventional method (additional delay: 200 ms).



(a) Rubber ball



(b) Soft tennis ball

**Figure 11.** Force in proposed method (additional delay: 200 ms).

when the additional delay is 0 ms, we can see similar tendencies between the conventional method and the proposed method. Since the force of the haptic interface device and that of the robot arm are very different when the object is the rubber ball or the soft tennis ball, it is easy to identify the ball by the perceived softness, and the average of correct answer rate is almost 100%. From **Figure 10** and **Figure 11**, we find that the force of the haptic interface device and that of the robot arm are very different from each other when the balls are different in the proposed method. Therefore, the average of correct answer rate of the proposed method is higher than that of the conventional method. However, from **Figure 10** and **Figure 11**, we see that when the object is the rubber ball, the force of the haptic interface device is more close to the real feeling of pushing the ball in the proposed method. However, when the object is the soft tennis ball, the force of the haptic interface device in the proposed method is more close to the real feeling of pushing the ball in the conventional method. In the proposed method, the subject felt larger reaction force which is opposite to the movement direction always, and it is difficult for the subject to perceive the softness of the ball.

From above discussion, we can say that the proposed method is more suitable for objects with certain hardness, and the conventional method has much better effects when the objects are not so hard.

## 6. Conclusions

In this paper, we applied stabilization control using the wave filter together with the phase control filter which was previously proposed by the authors to the remote robot system with force feedback and proposed a method to enhance haptic quality. We carried out the experiment to investigate the effect of the proposed method and compare the effect with that of the conventional method. As a result, the proposed method is more suitable for objects with certain hardness, and the conventional method has much better effects when the objects are not so hard.

As the next step of our research, we need to clarify the effective domain by carrying out other types of work such as writing characters. It is also important to study QoS control and stabilization control together in multiple remote robot systems with force feedback.

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## Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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